The effects of a cycling warm-up including high-intensity heavy-resistance conditioning contractions on subsequent 4 km time trial performance

ABSTRACT

Prior exercise has been shown to improve subsequent performance via different mechanisms. Sport-specific conditioning contractions can be used to exploit the 'post-activation potentiation' (PAP) phenomenon to enhance performance although this has rarely been investigated in short endurance events. The aim of this study was to compare a cycling warm-up with PAP-inducing conditioning contractions (CW) with a moderate intensity warm-up (MW) on performance and physiological outcomes of 4 km time trial. Ten well-trained male endurance cyclists ($\dot{V}O_{2max}$ 65.3 ± 5.6 ml·kg^{-1}·min^{-1}) performed two 4 km cycling time trials following a 5-minute recovery after a warm-up at 60% of $\dot{V}O_{2max}$ for 6.5-minutes (MW), and a warm-up with conditioning contractions (CW) consisting of 5 minutes at 60% of $\dot{V}O_{2max}$ then 3 x 10-seconds at 70% of peak power interspersed with 30-seconds recovery. Blood lactate concentrations were measured before and after time trial. Expired gases were analysed along with time, power output (PO), and peak forces over each 500 m split. Following CW, mean completion time was reduced (1.7 ± 3.5 s $p > 0.05$), PO increased (5.1 ± 10.5 W $p > 0.05$) as did peak force per pedal stroke (5.7 ± 11 N $p > 0.05$) when compared to MW. $\dot{V}O_2$ increased (1.4 ± 1.6 ml·kg^{-1}·min^{-1} $p < 0.05$) following CW, whilst RER decreased (0.05 ± 0.02 $p < 0.05$). Physiological and performance differences following CW were greatest over the first 1500 m of the trials. The results suggest a PAP-inducing warm-up alters $\dot{V}O_2$ kinetics and can lead to performance improvements in short endurance cycling but work and recovery durations should be optimised for each athlete.

KEYWORDS

Potentiation, PAP, power, prior-exercise, track, pursuit

INTRODUCTION

Before athletic events most competitors will perform a warm-up routine in the expectation that it will enhance their performance (3). Mechanisms found to improve performance include, but are not limited to, the speeding up of oxygen uptake ($\dot{V}O_2$) kinetics (6) and improving efficiency by reducing the oxygen cost of performance (1). Warm-ups also risk negatively affecting performance should they induce fatigue by being too intense (31) having insufficient recovery before the event (24). One contemporary technique undergoing scrutiny in the search for performance gain is post-activation potentiation (PAP).

PAP is a phenomenon where the performance of a muscle is enhanced by its recent contractile history (17) resulting in an increase of peak torque (12), an increased rate of force development (RFD) (12), a decrease in the time to peak torque (12, 22) and a change in pennation angle (35). The mechanism most often suggested as the explanation for the phenomenon is the phosphorylation of myosin regulatory light chains (RLC) (23), which results in the actin-myosin interaction becoming more sensitive to calcium ions released from the sarcoplasmic reticulum (30). This is thought to increase the rate of the cross bridging action, effectively increasing the RFD (17). PAP has been shown to be more pronounced in type II muscle fibres (15) due to their higher levels of myosin light chain kinase (28). Furthermore, Sale (29) proposed that PAP would be beneficial to endurance performance where submaximal forces are repeatedly exerted, invoking the low frequency tetanic contractions where calcium sensitivity is a factor and have been found to produce an increased RFD (36).

Although prior activation of a muscle beneficially induces PAP, there is also the coexisting effect of fatigue to be considered, which can produce a net negative effect on performance (24, 27, 31). The balance of PAP and fatigue was evident in the study by Chiu (7), which found that the training status of subjects influenced the overall response to PAP with *athletes* displaying enhanced performance compared to *recreationally trained* subjects. Hamada (14) also suggested that endurance trained subjects had enhanced fatigue resistance and an increased number of myosin light chains in the type I muscle fibres within the trained muscle groups, thereby enhancing the PAP response. These studies (7, 14) suggest that endurance trained athletes would benefit by both an enhanced PAP response and a reduction in fatigue despite having a predominance of type I muscle fibres, however few studies have investigated PAP in relation to short endurance events (1, 11, 16).

Typically, PAP-inducing protocols have used heavy resistance exercise (HRE), often in repeated bouts of muscle activity lasting 10-seconds (37). Intermittent conditioning activities have also been shown to induce PAP (2), leading to recent studies using sport-specific conditioning contractions to induce PAP (11, 16, 33), whilst maintaining protocols analogous to the typical HRE inducements. A feature of the Barnes et al. (1) study was the investigation into the oxygen cost of exercise after a PAP-inducing protocol, albeit only measured at submaximal levels. $\dot{V}O_2$ is a performance-limiting component of endurance, and as such characterises many endurance performance based studies (8, 21), but as yet, owing to the lack of research, no inferences can be drawn as to the positive or negative effects of PAP-inducing warm-ups on the oxygen cost at peri-maximal and supra-maximal intensities.

There have been many studies into the effects of warm-up routines, but not PAP per se (5, 13, 25, 38), demonstrating how they can elicit power and speed improvements in endurance cycling, particularly in the early stages of performance. The 4 km individual track pursuit race is a short endurance event, raced in the manner of an individual time trial, performed at supra-maximal intensity in terms of $\dot{V}O_{2,}$ with an estimated 85/15 aerobic/anaerobic energy contribution (20) making it a potential candidate for the positive effects of PAP. In particular, it seems likely that such a benefit would be evident in the early stages of the event prior to the self-perpetuating component being established, and where a small performance gain, such as 1 second, could be a race-winning margin.

A performance gain in a race such as the 4 km pursuit is measured in time, however speed and completion time are a function of power output (PO) (20), which in turn is derived from the force-angular velocity relationship in pedalling (32). The effects that PAP might have on force, power and the energy systems at supra-maximal intensities warrant further investigation. The principal aim of this study was to compare a cycle specific warm-up including PAP-inducing conditioning contractions with a moderate intensity warm-up to determine whether there is a performance benefit in well-trained cyclists over a 4 km time trial. Specifically, it was hypothesised that the PAP warm-up would enhance force, PO and time over the 4 km trial, particularly over the early stages. In addition, the study examined the effects of these warm-ups on specific physiological measures that relate to overall performance.

METHODS

Experimental Approach to the Problem

In a repeated measures counter-balanced design, subjects visited the laboratory on three separate occasions over a maximum of 10 days. During the first visit they undertook a graded incremental cycling test to exhaustion to determine PO intensities relative to $\dot{V}O_{2max}$ and a cycling maximum power test, to determine individual intensities for use in the experimental trials. After a rest period of approximately 30 minutes, subjects then completed a familiarisation of the experimental trial conditions. Between 2 and 7 days later the subjects returned for their first experimental trial; 24–96 hours after that they undertook their final and alternate experimental trial. The experimental trials were randomised in order and consisted of either the moderate intensity warm-up and a 4 km time trial, or the warm-up including high-intensity conditioning contractions and a 4 km time trial.

Subjects were asked to refrain from alcohol and caffeine on the day of any sessions, not to have eaten two hours beforehand or undertaken any strenuous exercise in the preceding 24 hours. The two experimental sessions were conducted at approximately the same time of day (within 2 hours) for each subject under similar air-conditioned environmental conditions (19–22 °C) within the Department of Sport and Exercise Science’s Research Laboratory. The two ergometers used in the sessions were set up based on measurements the subjects supplied from their own bicycles, which were then replicated in subsequent sessions. Subjects also used their own shoes and preferred pedal type throughout.

The key dependent variables measured during the 4 km trials were time, PO and peak force per pedal stroke. Other physiological and perceptual markers of performance measured were $\dot{V}O_2$, volume of carbon dioxide expired ($\dot{V}CO_2$), blood lactate concentration ($[La^-]_b$), heart rate (HR), ratings of perceived exertion (RPE) on a scale of 6 to 20 (4) and leg pain on a 1 to 10 scale (9).

Subjects

Ten healthy males from regional cycling and triathlon clubs and teams were invited to participate in, and successfully completed this study, (mean ± SD; age 32.2 ± 10.7 years; stature 181.8 ± 7.5 cm; mass 71.7 ± 6.6 kg), which had prior faculty ethics committee approval. The subjects were well-trained endurance cyclists, experienced at time trials and competing in open regional, national and international age group races ($\dot{V}O_{2max}$ 65.3 ± 5.6 $ml \cdot kg^{-1} \cdot min^{-1}$; training volume 8.4 ± 2.6 $hours \cdot week^{-1}$; training experience 8.2 ± 6.0 years). All subjects gave written informed consent prior to their participation. Before each exercise session subjects completed a health screening questionnaire and received a detailed explanation of the session, along with instruction on how to interpret and use the RPE and leg pain scales.

Procedures

Baseline Test. A graded incremental cycling test was performed on an electronically braked ergometer (Lode Excalibur Sport, Lode BV, Groningen, Netherlands). Cycling commenced at 120 W at a self-selected cadence and was increased by 30 W every 3 minutes until volitional exhaustion. $[La^-]_b$ was measured in the final 30 seconds of each stage via a finger-tip blood sample (Lactate Pro II, Arkay, Kyoto, Japan), together with the subject’s RPE. Pulmonary gas exchange was measured using an online gas analysis system (Oxycon Pro, Viasys Healthcare, Hochenberg, Germany), which was calibrated automatically prior to the test with ambient air, humidity readings and gases of known concentrations. $\dot{V}O_2$ was measured breath-by-breath and averaged over each 30-second epoch. $\dot{V}O_{2max}$ was determined as the largest of the averaged values recorded and in accordance with the British Association of Sport and Exercise Sciences criteria (40). The $\dot{V}O_2$ for each stage was defined as the average $\dot{V}O_2$ recorded in the final minute. Lactate threshold was determined as the PO when $[La^-]_b$ exceeded 1.0 mmol·l^{-1} above baseline values (10). PO at 60% of $\dot{V}O_{2max}$ was determined using linear interpolation of the PO during of the two stages that eliciting $\dot{V}O_2$ closest to 60% of the measured $\dot{V}O_{2max}$. This was checked to confirm it was below the lactate threshold for each subject and hence in the moderate intensity domain (26).

Following a rest of approximately 30 minutes, two maximum power cycling tests were performed on a Wattbike Pro cycle ergometer (Wattbike Ltd., Nottingham, UK). The Wattbike has been shown to be reliable when used by trained cyclists with a CV of 1.8% at 300 W (18). Following a brief warm-up, the subjects performed two 6-second sprints separated by approximately 5 minutes. Peak power (PP) was recorded as the maximum PO reached during the two attempts. A value equating to 70% of PP was then recorded for use in the later experimental trials in order to invoke a PAP-inducing near maximal voluntary contraction (37).

Familiarisation Trial. The familiarisation trial was conducted after the baseline tests and followed the same procedure as the CW experimental trial (described below), with the exception of allowing the subject to adjust the resistance setting of the Wattbike during the first half of the trial to allow for a self-selected preferred cadence for this duration of trial. The setting used for the second half of the trial was noted and applied for that subject's later experimental trials.

< Figure 1 near here >

Experimental Trials. During each experimental trial the subject completed either a MW or CW on the Lode ergometer followed by a 5-minute passive recovery and a 4 km time trial on the Wattbike Pro. Warm-up intensities were fixed using the cadence independent hyperbolic mode of the Lode ergometer. MW consisted of a 6.5-minute cycle at the PO calculated to elicit 60% $\dot{V}O_{2max}$. CW consisted of a 5-minute cycle at the same PO eliciting 60% $\dot{V}O_{2max}$, immediately followed by three bouts of 10 seconds at a power equal to 70% PP, with 30 seconds passive recovery between bouts (Figure 1). Subjects were instructed to remain seated and aim for a slow cadence of 60 $r{\cdot}min^{-1}$ for the 10-second bouts so as to attain a series of near maximal voluntary contractions, and their usual preferred cadence at other times. Following 5 minutes of passive recovery subjects were instructed to perform the 4 km time trial as if it were a race by completing the distance in the shortest possible time, using the drop handlebar position. The resistance setting selected during familiarisation was used during the 4 km trials to allow for the subjects preferred cadence (103.6 ± 2.5 $r{\cdot}min^{-1}$). No adjustments were allowed during the experimental trials. Subjects were asked not to vary their approach to pacing between the experimental trials. All instantaneous details of speed, power, time and cadence were withheld from the subjects in order to minimise self-pacing cues. Subjects were verbally informed of their elapsed distance after each 500 metres so as to avoid misjudging the end of the test. Non-specific verbal encouragement was given throughout. $[La^-]_b$ was taken from finger-tip samples at rest, 60 seconds prior to the start of, and 15 seconds after completing the trial. After each km of the 4 km trial the subject was asked to indicate their RPE and leg pain. HR via a chest strap (Polar Electro Oy, Kempele, Finland) and breath-by-breath pulmonary gas exchange were recorded throughout the 4 km trial. The Wattbike Pro calculated distance and recorded time, power, cadence and force dynamics for each pedal revolution throughout the trials. Split times for each 500 metres were computed from the Wattbike Pro data using custom built spreadsheets in Microsoft Excel 2013 (Microsoft Corp., California, US) and interpolation of the elapsed times of pedal strokes. Force, PO, $\dot{V}O_2$, $\dot{V}CO_2$ and HR were also computed using custom spreadsheets to extract data for each 500 m split.

Statistical Analyses

Descriptive statistics (mean ± SD) were calculated for each dependent variable across each trial. The normality of distributions of the dependent variables was confirmed using the Shapiro-Wilk statistic and inferential statistics were used to test the main research hypotheses. Specifically, paired sample *t*-tests were used to assess differences between the trials due to the condition type (MW/CW) for the following variables: completion time; PO; peak force per pedal stroke; $\dot{V}O_2$, $\dot{V}CO_2$, RER, HR, resting $[La^-]_b$, $[La^-]_b$ 60 seconds before the start of the trials and $[La^-]_b$ 15 seconds after completion of the trials. Two-way repeated measures ANOVA were performed to assess the variability of the mean scores due to condition type (MW/CW) and distance (1 km splits over 4 levels for RPE and leg pain, 500 m splits over 8 levels for completion time, PO, peak force per pedal stroke, $\dot{V}O_2$, $\dot{V}CO_2$, RER, HR). Sphericity was checked with Mauchly's test and accounted for where necessary using the Greenhouse-Geisser adjustment. Paired sample *t*-tests were used post-hoc where appropriate on pair-wise conditions. Statistical significance was set at $p < 0.05$ throughout, with Bonferroni corrections where appropriate. Analysis was performed using SPSS v.21 (IBM Corp., Armonk, NY, US). Effect sizes (ES) ± 90% confidence intervals were calculated by dividing the mean of the differences due to the conditions by the pooled SD from the trials and classified as trivial < 0.2; small < 0.6; moderate < 1.2; large < 2.0; very large ≥ 2.0 (19).

RESULTS

It was observed that CW led to a *small* but non-significant ($p > 0.05$) reduction in completion time of 1.7 ± 3.5 s over the 4 km time trial (Table 1), and *small* but non-significant increases in mean PO (5.1 ± 10.5 W) and mean peak force per pedal stroke (5.7 ± 11.0 N). Figure 2 shows the individual responses to the conditioning warm-up in terms of completion times with seven out of ten subjects completing the 4 km trial faster after CW. The physiological measures taken over the 4 km time trials are shown in Table 2. Mean $\dot{V}O_2$ was significantly elevated following CW compared to MW by 1.4 ± 1.6 $ml \cdot kg^{-1} \cdot min^{-1}$, as was HR by 4.0 ± 3.3 $b \cdot min^{-1}$, whilst RER decreased significantly by 0.05 ± 0.02. A *very large* significant increase in $[La^-]_b$ was seen following CW compared to MW of 3.7 ± 1.4 $mmol \cdot l^{-1}$ 60 seconds prior to the start of the 4 km trials, however upon completion the difference had been reversed (-1.5 ± 2.7 $mmol \cdot l^{-1}$).

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For the 500 m splits no significant (p > 0.05) interactions between split and warm-up condition for time, power, peak pedal forces or HR were observed. ANOVA of expired gases did reveal significant (p < 0.01) split x warm-up condition interactions for both $\dot{V}O_2$ and RER, but no significant interaction effect including $\dot{V}CO_2$ (p > 0.05). As can be seen in Figure 3, $\dot{V}O_2$ rose at a faster rate whilst RER was suppressed following CW. Post-hoc analysis of the first three 500 m splits revealed significant increases in $\dot{V}O_2$ during splits 2 and 3 (p < 0.017), and decreases in RER during splits 1, 2 and 3 (p < 0.017). Whilst notable and expected increases in both RPE and leg pain scores were evident as the time trial progressed (Table 3), no significant interactions of condition and 1 km splits were observed.

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< Table 4 near here >

Post-hoc analysis of time, power, peak pedal forces, $\dot{V}$O2 and RER were undertaken on the first 1500 m of the trials as the greatest differences in performance were seen during the initial stages following the warm-up conditions (Table 4). Whilst a *small* difference in time to 1500 m (1.2 ± 1.5 s), and a *small* increase in mean power (10.4 ± 13.3 W) between the trials were detected over this initial period, the differences were not significant.

DISCUSSION

The main hypothesis for the study was that the conditioning warm-up would improve completion time, power output and peak forces during the 4 km time trials. Although mean completion time was reduced by 1.7 s, mean power output by 5.1 W and mean peak force by 5.7 N, the results did not attain statistical significance. The mean increase in power output following CW however, did exceed the 5 W increase suggested to show a true increase in trained cyclists on a Wattbike (18). Whilst the effect sizes of these improvements are *small*, they are substantial in relation to competition events and surpass the gold medal race winning margins of less than 0.5 seconds in both the 2014 and 2015 4 km individual pursuit World Championships. Similarly, the performance differences due to the warm-ups tended to be greatest over the initial 1500 m of the trials and accounted for 1.2 seconds of the overall mean reduction in time. However, it is unclear if the peak forces applied to the pedals during each pedal stroke were responsible per se, or whether the increased forces necessary to generate the additional power were distributed through the pedal stroke.

The high-intensity, heavy-resistance conditioning contractions performed in CW were intended to elicit PAP in the muscles used in the pedalling action. Similar to a number of other studies (1, 11, 16, 33) the magnitude of PAP was not directly measured following the complex actions, however the presence of the potentiating effect is assumed due to the near maximal voluntary contractions undertaken (12, 35, 37). Notwithstanding the non-significance of the improvements found in the present study, the effects of CW are similar to the findings of other studies in short endurance events designed to invoke PAP which have shown performance improvements in rowing (11), swimming (16, 33) and running (1). Where split times have been considered during the trials (11, 16), the improvements in time and power have been more pronounced during the earlier splits, supporting the proposition by Sale (29) that any muscle activity will induce PAP, and that once initiated in an endurance event the effects of PAP would be ongoing owing to the exercise itself. The neuromuscular effects of PAP include increased calcium sensitivity of the myosin light chain (36), possibly explaining increases in power following conditioning contractions. Whilst a small increase in power was found in this study following CW, changes to the peak force per pedal stroke were less clear. As PAP also modifies muscle twitch properties by increasing the rate of force development (12, 17), reducing time to peak torque (12, 22), and reducing half-relaxation time (12), potentially it yields higher forces being generated sooner and distributed over a greater portion of the pedal stroke rather than increasing peak forces.

The effectiveness of the CW in this study appeared to be individualistic despite the subjects being of similar fitness, training background, and standard. Whilst training status (14) and muscle fibre type (15, 28) have been shown to influence the effects of PAP and fatigue (7, 27), there is no method of accurately quantifying their interaction on the balance of these opposing effects. The magnitude of the PAP effect was not measured by electromyography in this study and doing so in future studies could help maximise the positive effects of PAP on an individual basis, and help control the parameters of the balance of PAP and fatigue. The rest interval between the PAP inducement and exercise trial is critical to this balance and as a number of different rest periods from 2-18 minutes have been trialled for different activities with varying results (39), it would seem that optimisation on an individual basis by trial and error is needed to ensure performance improvements.

Whilst the current performance changes observed following CW were suggestive of PAP, they were accompanied by changes in the physiological measures of $\dot{V}O_2$, HR, RER, and $[La^-]_b$, which also offer a potential explanation for the changes. A moderate elevation of $[La^-]_b$ has been linked with an improvement in subsequent endurance performance (6, 21, 25, 38), possibly inducing a protection against fatigue (21). Despite an increase in $[La^-]_b$ Burnley et al. (6) found a performance reduction following 30 seconds of sprinting prior to a short cycling time trial. However, whilst the high-intensity sprint warm-up produced similar metabolic responses, the high cadences are unlikely to have elicited a similar PAP response as the present study. The particular early stage increase in $\dot{V}O_2$ in the present study mirrors that in many studies exhibiting improved performance following effective prior exercise (5, 8, 13, 25) and would appear to be a highly desirable effect of a high-intensity warm-up. It has also been speculated that increased muscle temperature may be associated with changes in oxygen kinetics (5), however the measurement of muscle temperature was beyond the scope of the present study. This relationship between $\dot{V}O_2$ and PAP is opposite to that reported by Barnes et al. (1) who found a lower oxygen cost following PAP-inducement in sub-maximal exercise. It is possible that this discrepancy reflects the differences in intensity at which $\dot{V}O_2$ was measured, with the supra-maximal exercise in the current study eliciting $\dot{V}O_2$ values at or very close to each person's $\dot{V}O_{2max}$.

Accompanying the elevated $\dot{V}O_2$ following CW was a reduced $\dot{V}CO_2$ and a moderate reduction in RER, both in the first 1500 m and throughout the 4 km time trial, together with a lower $[La^-]_b$ upon completion of the 4 km time trial, suggesting a reduced reliance on energy derived from anaerobic pathways (34). It is somewhat surprising that a more noticeable difference in PO was not evident rather than the apparent sparing of anaerobic resources. Quantifying the anaerobic contribution cannot be done by measurement, and calculations of the anaerobic contribution in supra-maximal exercise contain major sources of error (25), hence the inferences about anaerobic contribution in this study are drawn from pulmonary gas exchanges and the $[La^-]_b$ measurements previously mentioned. It is possible that pacing cues and effort perception prevented any uprating of PO during either trial until the final seconds regardless of remaining anaerobic capacity. Adherence to a preferred pacing strategy along with measures of RPE and leg pain that increased throughout each trial may have restricted the raising of PO more so than the availability of anaerobic resources. Instantaneous performance measures were withheld from the subjects, however the sound from the airbrake of the Wattbike offered continuous feedback of any change of cadence or power. This feedback could also have influenced pacing and consequently the anaerobic contribution, particularly in the latter stages of the trial as the subject’s focus may have been on maintaining cadence rather than increasing it.

The effect of this high-intensity heavy-resistance conditioning warm-up is similar to the effects found in other warm-up routines that have included PAP inducing contractions (11, 16, 33), and those that have associated performance improvement with metabolic factors following high-intensity warm-ups or repeated sprints (13, 21, 25). Whether PAP can be used to complement existing routines, in order to enhance the neuromuscular responses as well as the metabolic responses, and so compound performance improvements warrants further research. Investigations into complex warm-up routines incorporating PAP should also look at the individual responses to the PAP-fatigue balance and recovery times.

PRACTICAL APPLICATIONS

This study indicates that a warm-up routine that includes PAP-inducing conditioning contractions can have a beneficial and worthwhile effect on cycling performance. The study also emphasises the need for coaches and athletes to optimise the balance of PAP and fatigue, by variation of recovery and work intervals on an individual basis. As the effects tended to be greatest over the first 1500 m (or approximately 80 seconds), the inclusion of conditioning contractions alongside a traditional metabolic warm-up would be most beneficial in the short duration endurance track racing of 4 km or less, such as the individual pursuit or ‘kilo’. The high-intensity, heavy-resistance efforts can be reproduced using readily available turbo-trainers meaning that all athletes can easily implement the protocol immediately prior to competition.

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FIGURES

Figure 1: Schematic showing the timeline for both experimental trials

<fig1.pptx>

Figure 2: Individual changes in completion time for the 4 km time trial. A positive time difference indicates that the subject was faster following the conditioning warm-up than the moderate warm-up.

<fig2.pptx>

Figure 3: Changes in a) oxygen uptake and b) RER for each 500 m split of the 4 km time trials. Differences ($p < 0.05$) were due to the main effects of condition, split number, and their interactions. Plot values are mean ± SD

<fig3.pptx>